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Copula based drought frequency analysis considering the spatio-temporal variability in Southwest China

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SUMMARY

Drought frequency analysis is a prerequisite for drought resistance planning and drought risk management. Drought is a spatio-temporal dynamic process, usually characterized by its duration, spatial extent, and severity. Copula based multivariate frequency analysis has been widely used to calculate drought frequency. However, the spatial extent is scarcely considered in previous studies, due to the fact that drought event is usually identified either for a fixed spatial scale or for a fixed temporal scale. This study develops a regional drought frequency analysis model based on trivariate copulas by considering the spatio-temporal variations of drought events. Drought duration, drought affect area, and drought severity are identified first, and their trivariate joint distribution is constructed later. The model is applied for drought frequency analysis in Southwest China during 1961–2012. A variety of probability distribution functions and copula functions (including elliptical, symmetric and asymmetric Archimedean) are used as candidate choices, and the most appropriate ones are selected based on goodness of fit using different methods. The robustness of drought frequency analysis is then evaluated and discussed. The results show that drought frequency analysis needs to fully consider the three characteristic parameters (duration, affect area, and severity) reflecting drought spatio-temporal variability. And the drought return period estimated by the copula-based trivariate frequency analysis appropriately integrates the effects of drought duration, affect area and severity, which is a reliable drought statistical measurement. The 2009–2010 drought, which has a return period of about 94 years, is the most severe one in Southwest China during the period of 1961–2012. The Joe and Gumbel copulas are found to be more suitable to estimate the joint distribution of drought duration, affect area and severity, and the Asymmetric (nested) function forms perform better than the symmetric functions.

1. Introduction

Drought is water deficiency in a prolonged period compared with normal condition. It can last for several weeks, months, even years, affect a large area, and have devastating impacts on agriculture, water resources, environment and human lives, making it the costliest and most widespread natural disaster (Wilhite, 2001; Bryant, 2004). Drought frequency analysis (particularly for the extreme droughts) is useful for selecting drought-relief measures and for drought risk management.

Drought identification and characterization is a prerequisite to drought frequency analysis. In general, drought is often characterized by its duration, severity, intensity and spatial extent (Mishra and Singh, 2010). Yevjevich (1967) proposed the one-dimensional truncation method to extract drought duration, severity, and intensity from drought index sequence. But this method discards much of the spatio-temporal information by reducing drought events to a one dimensional subspace, thereby not enabling to capture the real drought structure in space–time dimensions. Andreadis et al. (2005) proposed a clustering algorithm to extract the voxels of drought connected in space. Lloyd-Hughes (2012) extended the clustering algorithm to 3-dimensional space (longitude, latitude, and time), fulfilled the complete spatio-temporal representation of the drought event. On this basis, Xu et al. (2015) proposed a 3-dimensional drought identification scheme and used it to analyze the spatio-temporal variation of drought in China during 1961–2012.

Since droughts are multivariate phenomenon, the univariate frequency analysis method is inadequate to describe their probabilistic nature. Many efforts have been devoted to derive the bivariate and multivariate joint distributions of drought

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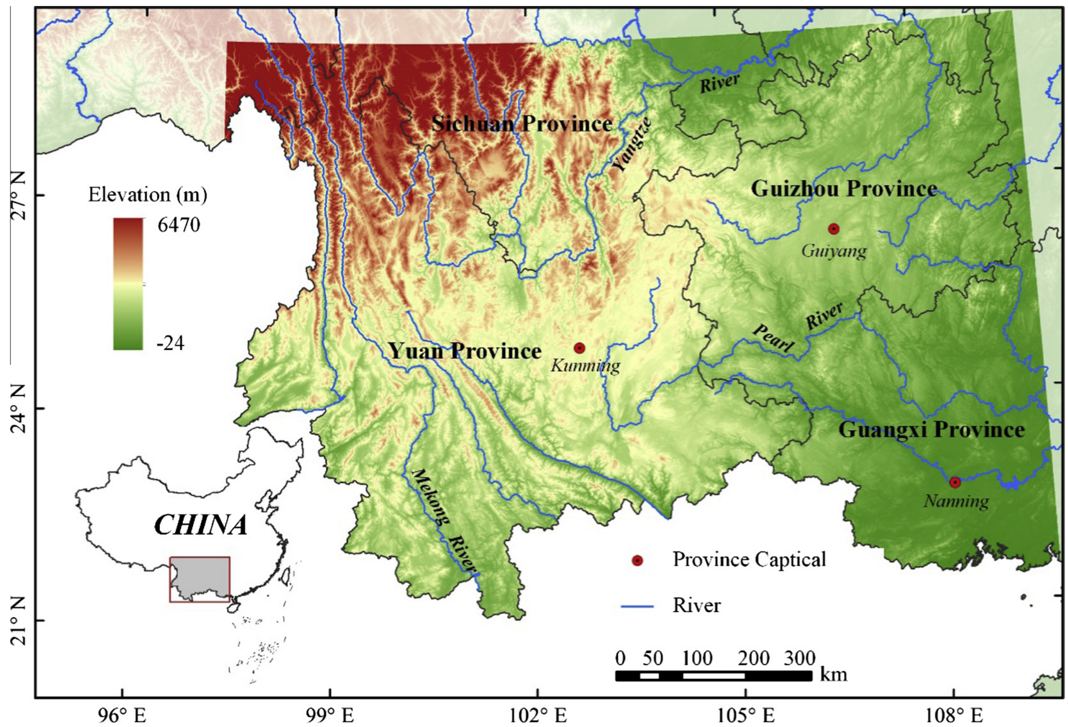

Fig. 1. Location and topography map of Southwest China.

characteristic variables. Conventionally, joint distributions are analytically acquired, by either assuming drought characteristics to be independent identically random variables (Cancelliere and Salas, 2004), or assuming that they obey the same univariate distribution and have explicit multivariate forms (e.g. multivariate normal, multivariate exponential, multivariate gamma) (Shiau, 2006). However, these two assumptions are not satisfied in most cases, because the drought characteristic variables are highly correlated and may obey different univariate distributions. In addition, the nonparametric kernel estimator method (Kim et al., 2003) and entropy-based method (Hao and Singh, 2012) are also used to derive the joint distribution of duration and severity.

Copula theory, initially introduced by Sklar (1959), has been widely used in bivariate and multivariate drought frequency analysis. Copulas functions build multivariate joint distribution from the univariate distributions based on the dependence structure among random variables. A comprehensive and detailed introduction of the copula theory can be found in previous studies by Joe (1997) and Nelsen (2007). Copulas can deal with combination of margins because of the margin-free characteristics due to use of ranks for estimating parameters (Kojadinovic and Yan, 2010). The commonly used copulas belong to four types: elliptical type (normal and student t), Archimedean type (Clayton, Gumbel, Joe, Frank, and AMH), extreme value type (Gumbel, Husler-Reiss, Galambos, Tawn, and t-EV), and miscellaneous type (Plackett and Farlie–Gumbel–Morgenstern). Lots of studies have focused on the copula-based drought frequency analysis. For example, in bivariate context, Shiau (2006) used five bivariate copulas to construct a joint distribution between drought duration and severity. Wong et al. (2013) investigated the cross-dependence between meteorological and hydrological drought based on bivariate copulas. In trivariate context, Song and Singh (2009) constructed the joint distribution of drought duration, severity, and interval time, using elliptical copulas. Ma et al. (2013) used elliptical copulas, symmetrical and asymmetrical Archimedean copulas to construct a trivariate joint distribution of drought duration, severity and peak. Madadgar and Moradkhani (2011) constructed the trivariate joint distribution of drought duration, severity, and intensity, and evaluated the impact of climate change on future droughts based on general circulation models (GCMs) outputs. For higher dimensions, Chen et al. (2013) constructed a four-dimensional joint distribution of drought duration, interval time, severity, and minimum SPI (Standardized Precipitation Index) values based on elliptical and Archimedean copulas. These studies commonly considered drought duration and severity, however few studies considered drought affected area in frequency analysis. Among the copulas-based drought frequency analysis, Elliptical and Archimedean copulas were the most popular used equations. The inversion of Kendall's τ (itau) method was usually used to estimate the parameters of probability distribution, and the goodness of fit (GOF) for probability distribution was usually tested by the least root mean square error (RMSE), Kolmogorov–Smirnov (KS) test, Cramér-von Mises (CM) test, Anderson–Darling (AD) test based on Akaike information criterion (AIC) and Bayesian information criterion (BIC) (Genest et al., 2009; Li et al., 2013).

Such a variety of studies have focused on copula based drought frequency analysis, but they usually use the areal average values of drought characteristics. Few have considered drought affect area which is one of the most important drought characteristic variables, because the drought identification method employed in most previous studies could not extract the spatio-temporal characteristics. Another problem in copula-based drought frequency analysis is how to choose appropriate margin probability distribution and copula functions. Since many choices of marginal probability distributions, copula functions, and GOF test methods are potentially usable in drought frequency analysis, the final selections may be different depending on the different candidate margins, copulas, and GOF criteria. Therefore, it is necessary to evaluate the sensitivity of drought frequency analysis method to the selection of margins and copulas.

In the paper, we focus on copulas based multivariate drought frequency analysis considering drought duration, affect area, and